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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

PREDICTION MODELING OF PHYSIOLOGICAL RESPONSES

AND HUMAN PERFORMANCE IN THE HEAT

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Running Head: Computer Prediction Modeling

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INTRODUCTION

Over the last two decades, the Military Ergonomics Division of the US Army Research Institute of Environmental Medicine has been establishing the data base and developing a series of predictive equations for deep body temperature, heart rate and sweat loss responses of clothed soldiers performing physical work at various environmental extremes. Individual predictive equations for rectal temperature (Givoni and Goldman, 1972), heart rate (Givoni and Goldman, 1973a) and sweat loss (Shapiro et al., 1982) as a function of the physical work intensity, environmental conditions and particular clothing ensemble have been published in the open literature. In addition, important modifying factors such as energy expenditure (Pandolf et al., 1977a), state of heat acclimation (Givoni and Goldman, 1973b) and solar heat load (Breckenridge and Goldman, 1971) have been evaluated and appropriate predictive equations developed. Suitable data bases to evaluate the predictive importance of cardiorespiratory physical fitness (Pandolf et al., 1977b; Shapiro et al., 1980b), gender (Shapiro et al., 1981; Sawka et al., 1983) and state of hydration (Sawka et al., 1983; Sawka et al., 1984) have been established.

Over this same time period, our Division has also attempted to program these predictive equations on various desk top and hand held calculators with the express purpose of developing a

comprehensive heat stress model for predicting soldier performance to work, clothing and the environment. The initial computer programming was conducted on a Hewlett Packard 9810A desk top calculator with the outputs being the predicted rectal temperature and heart rate responses. As the technology advanced, we adapted these computer programs for the card reading Hewlett Packard 65 hand held calculator with similar outputs to those of the desk top version. Currently, we have developed a more comprehensive model which is programmed on a Hewlett Packard 41 CV hand held calculator. The current model deals with the interaction of various multi-disciplinary factors such as (a) the theoretical physics of heat transfer, (b) the biophysics of clothing, (c) the physiology of metabolic heat production, distribution and elimination, and (d) related meteorological considerations. The primary physiological inputs are deep body (rectal) temperature and sweat loss while the predicted outputs are the expected physical work-rest cycle, the maximum single physical work time if appropriate, and the associated water requirements.

This paper presents the mathematical basis employed in the development of the various individual predictive equations of our heat stress model. In addition, our current heat stress prediction model as programmed on the HP 41 CV is discussed from

the standpoint of propriety in meeting the Army's needs and therefore assisting in military mission accomplishment.

MATHEMATICAL BASIS

Unless otherwise stated, all terminology for abbreviations and units of measurement follow the usage recommended by the Système international d'unités (SI units) and the International Union of Physiological Sciences.

Rectal Temperature Prediction

The general formula for predicting the final equilibrium rectal temperature (T_{ref}) as suggested by Givoni and Goldman (1972) is

$$T_{ref}(^{O}C) = 36.75 + 0.004(M-W_{ex}) + 0.0011 H_{(r+c)} + 0.8e \exp[0.0047(E_{req}-E_{max})] \quad [1]$$

| Metabolic | Dry Heat Exchange | Evaporative Heat Exchange |

Equation 1 is comprised of three components

(1) the metabolic component $[36.75 + 0.004(M-W_{ex})]$

where $M = 1.5W + 2.0(W+L)(L/W)^2 + \eta(W+L)[1.5(V_w)^2 + 0.35GV_w]$ [2]

as originally published by Pandolf et al. (1977b)

and $W_{ex} = 0.098 G(W+L)V_w$ [3]

as suggested by Givoni and Goldman (1972)

where M = metabolic rate, (watt)

W_{ex} = external work, (watt)

W = nude weight, (kg)

L = clothing and equipment weight, (kg)

η =terrain factor

V_w =walking velocity, $(m \cdot s^{-1})$

G =grade, (%)

(2) the dry heat exchange component $[0.0011\ H_{(r+c)}]$

where $H_{(r+c)} = 6.45\ A_D(T_{db}-T_{sk})/I_t$ [4]

as inferred by Givoni and Goldman (1972)

where A_D =body surface area, (m^2)

T_{db}=dry bulb temperature, ($^\circ$C)

T_{sk}=skin temperature, ($^\circ$C)

I_t =total insulation, (clo)

(3) the evaporative heat exchange component $\{0.8e\ \exp[0.0047(E_{reg}-E_{max})]\}$

as indicated by Givoni and Goldman (1972)

where $E_{req}=(M-W_{ex})+H_{(r+c)}$ [5]

and $E_{max}=14.21\ im/I_t\ A_{Deff}\ (P_{sk}-\phi_a P_a)$ [6]

where e   = base of natural log

i_m = permeability index

A_{Deff}= effective surface area for evaporation, (m^2)

P_{sk} = water vapor pressure at the skin, (mm Hg)

ϕ_a = relative humidity, (%)

P_a = saturated water vapor pressure of air at T_{db}, (mm Hg)

and other abbreviations as described above

In order to compute physical work-rest cycles, the time patterns of rectal temperature have been analyzed for three different conditions: (a) the time pattern for resting subjects

under various heat stress conditions referred to as <u>resting</u> T_{ret} (resting rectal temperature at any time t); (b) the elevation pattern for rectal temperature during physical work at the given climatic conditions referred to a <u>working</u> T_{ret} (rectal temperature at any time t after beginning physical work); and (c) the recovery rectal temperature after cessation of physical work referred to as <u>recovery</u> T_{ret} (rectal temperature at any time t after completion of physical work). These three equations have been presented and discussed in detail elsewhere (Givoni and Goldman, 1972).

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INSERT FIGURES 1 AND 2 ABOUT HERE

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Figure 1 presents a comparison of the predicted (lines) and measured (points) time patterns for rectal temperature during one hour cycles of rest, physical work and recovery as originally published by Givoni and Goldman (1972). These findings indicate that the rectal temperature patterns predicted from the proposed equations are in good agreement with the experimental observations which represent a wide range of metabolic rates, climatic conditions and clothing properties.

All of the predictive formulas for rectal temperature presented and discussed above pertain to an exercise-heat acclimated individual. In order to characterize the non- and

partially acclimated individual, these equations were modified for the purpose of describing the acclimation process as the final equilibrium rectal temperature or for the general time pattern of rectal temperature as $\Delta T_{ref(accl)}$ and $\Delta T_{ret(accl)}$, respectively (Givoni and Goldman, 1973b). Figure 2 illustrates mean daily patterns of rectal temperature during seven days of exercise-heat acclimation with the points representing the average measured values for 24 subjects (Givoni and Goldman, 1973b). In general, there is good agreement between the measured and predicted patterns.

Figure 3 shows the comparison of predicted and observed rectal temperature responses for 12 soldiers while wearing three different military clothing ensembles during tests under two different climatic conditions in Australia. These data which were collected by a group independent of our Institute are in quite good agreement with the predicted values, and in all but two instances, the observed responses are with $\pm$ 1 S.D. of predicted.

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INSERT FIGURE 3 ABOUT HERE

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Sweat Loss Prediction

The general equation for predicting sweat loss response (Δm_{sw}) as a function of exercise, environmental and clothing interactions as proposed by Shapiro et al. (1982) is

$$\Delta m_{sw}(g \cdot m^{-2} \cdot h^{-1}) = 27.9 \cdot E_{req} \cdot (E_{max})^{-0.455} \tag{7}$$

where Δm_{sw} = change in body weight from sweat loss;

and other abbreviations as described earlier.

This prediction equation was derived from over 250 experimental exposures to a wide range of climatic conditions (ambient temperature, 20-54°C and relative humidity, 10-90%) while wearing various clothing ensembles (light clothing and heavy clothing of high permeability or low permeability) at different metabolic rates (rest to moderate physical work). Therefore, this formula can be employed over a wide range of E_{req} (50-360, $W \cdot m^{-2}$) and E_{max} (20-525, $W \cdot m^{-2}$). In the present form, this formula is more applicable for predicting water requirements; however, it can be presented in appropriate units ($W \cdot m^{-2}$) for predicting the rate of sweat loss (Shapiro et al. 1982).

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INSERT FIGURE 4 ABOUT HERE

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A comparison of predicted and measured Δm_{sw} for 111 individual exposures is illustrated in Figure 4. These experiments considered ambient temperatures ranging from 35-49°C, relative humidities from 20-75%, different clothing ensembles and both resting and exercise evaluations. A correlation coefficient between the predicted and measured sweat loss of r=0.94 was observed over a wide range of sweating responses.

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INSERT FIGURE 5 ABOUT HERE

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Figure 5 displays a comparison of four different methods for predicting sweat loss utilizing the experimental findings of Shapiro et al. (1982). Lustinec's equation (1973) employs a linear correlation between sweat rate and E_{reg} for low skin wettedness but a non-linear correlation between sweat rate, E_{req} and E_{max} for high skin wettedness. Givoni and Berner-Nir (1967) developed a prediction equation for expected sweat rate structured from the exponential function of the ratic E_{req}/E_{max}. Macpherson (1960) developed the predicted four hour sweat rate index (P4SR) which incorporates ambient temperature, wet-bulb temperature, wind speed and correction for the particular clothing. With our equation, the predicted sweat loss was within the $\pm20\%$ range for 29 out of the 30 experimental conditions that were evaluated with only one condition ($37^{O}C$, 80% rh, walking in a sweat suit) greater than 20% from the measured value (r=0.95). Lustinec's equation showed 8 conditions out of the 30 beyond the $\pm20\%$ range (4 additional conditions were beyond the equation's range) while for Givoni and Berner-Nir's equation 14 conditions were out of the $\pm20\%$ range, and for the P4SR method 12 conditions were beyond the $\pm20\%$ range (2 additional conditions were beyond this nomogram's range). Thus, the present formula was seen to

predict sweat loss more accurately than other methods especially under extreme climatic conditions (Shapiro et al. 1982). However, these same authors state that the present prediction equation may have some limitations at very high sweat rates.

Heart Rate Prediction

The general formulas for predicting the final equilibrium heart rate (HR_f) as proposed by Givoni and Goldman (1973a) for heat acclimated individuals are

$$HR_f (bts \cdot min^{-1}) = 65 + 0.35(I_{HR} - 25) \text{ for } 25 \leq I_{HR} \leq 225 \qquad [8]$$

$$HR_f (bts \cdot min^{-1}) = 135 + 45[1 - e^{(0.01[I_{HR} - 225])}] \text{ for } I_{HR} \geq 225 \qquad [9]$$

where $I_{HR} = 100(T_{ref} - 36.75) + 0.4 W_{ex}$

The time patterns for heart rate responses of heat acclimated individuals necessary to predict work-rest cycles have been described for work and rest at any time t as working HR_t and resting HR_t, respectively (Givoni and Goldman, 1973a). In addition, these same authors have presented a formula to predict the time pattern for heart rate recovery from the cessation of physical work towards the appropriate equilibrium resting level as recovery HR_t (Givoni and Goldman, 1973a). Further, Givoni and Goldman (1973b) published a predictive equation to describe the equilibrium heart rate responses expected for non- and partially-acclimated individuals. The computational adjustments necessary to predict the time patterns of heart rate during rest, work and recovery from work for non- and partially-acclimated persons are also displayed in this same reference.

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INSERT FIGURE 6 ABOUT HERE

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A comparison between predicted and measured final equilibrium heart rate responses from our own investigations and the investigations of others (MacPherson, 1960; Wyndham et al., 1954) as originally presented by Givoni and Goldman (1973a) is shown in Figure 6. For both our own observations and the observations of others, the agreement between the measured and the predicted heart rate responses is excellent as shown in the figure.

CURRENT HEAT STRESS PREDICTION MODEL

As stated earlier, the current version of our heat stress prediction model is programmed on a standard Hewlett Packard (HP) 41 CV hand-held calculator. The only major modifications to the standard HP 41 CV involve (a) the addition of a specially designed portable eprom (Hand Held Products, Inc.) for 32K of added memory and (b) a redesigned touch pad. With the 32K of added memory, the HP 41 CV presents 36K of memory of which 8K is currently programmed. The redesign of the touch pad for the HP 41 CV to incorporate our heat stress prediction modeling needs is shown in Figure 7.

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INSERT FIGURE 7 ABOUT HERE

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As seen in Figure 7, the prefix keys ("select","disp","comp"and "disp units") are located near the center of the touch pad. Above these prefix keys the user observes keys for parameters which describe the soldier. The three rows of keys immediately below the prefix keys describe the environment. The bottom row of keys are output or information keys.

The top row of keys are used to set the computer programming parameters for the soldier's clothing system. Separate keys are designated for Mission Oriented Protective Posture (MOPP) levels I-IV which are based on the protective clothing and equipment worn. The various levels of MOPP provide a flexible clothing system to protect soldiers against suspected chemical agents during chemical warfare which may help facilitate mission accomplishment. In addition, 21 other clothing systems are available in a clothing menu which is displayed in Table 1. This table shows the description of the particular clothing system and the display given on the HP 41 CV. Each of the 25 clothing systems which are available to the user have individual coefficients which describe the thermophysical properties of the clothing as a function of the work rate and effective wind

velocity. This concept has been presented in some detail elsewhere (Givoni and Goldman, 1972).

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INSERT TABLE 1 ABOUT HERE

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The second row of keys from the top sets the internal parameters for the soldier's metabolic work rate. Individual keys are available to describe light, moderate and heavy work which are categorized as 250, 425 and 600 W, respectively. If another known metabolic rate is desired, it can be entered using the "metab rate" key. While the preferred units for metabolic rate are watt, values can be entered in $kcal \cdot hr^{-1}$, $BTU \cdot hr^{-1}$, or METS. This same key can be used to input the components necessary to compute the metabolic rate where body weight (kg), external load (kg), walking speed ($m \cdot s^{-1}$), grade (%), and a terrain coefficient are necessary (see Pandolf et al. 1977). The multiplication factors necessary to compute metabolic rate as a function of terrain are presented in Table 2. Finally, an additional key ("func") is available, but yet unprogrammed, to compute metabolic rate for other modes of locomotor than walking such as running, lifting, etc..

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INSERT TABLE 2 ABOUT HERE

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The third row of keys from the top are to individually categorize casualties ("caslt") as light, moderate or heavy, and to describe state of heat acclimation as either non-acclimated ("non-accl") or fully acclimated ("accl"). Light, moderate and heavy casualties are described as less than 5% casualties, about 20% casualties, and greater than 30% casulaties, respectively. These casualty categories are also based on individual upper limits for deep body temperature which were developed from information by Goldman (1981) and scientific results provided by Israel Defence Forces Technical Reports.

The first row of keys below the prefix keys address the ambient air temperature (T_a) and relative humidity (%rh). The T_a can be entered in either $^\circ$C or $^\circ$F while relative humidity can be evaluated as per cent relative humidity, wet bulb temperature ($^\circ$C or $^\circ$F), dew point or vapor pressure. If this information is not available to the user, input keys for our standard hot-wet (35°C, 75% rh) or hot-dry (49°C, 20% rh) climatic conditions are available.

The second row of keys below the prefix keys allow the user to provide input concerning the wind speed. While the preferred units are $m \cdot s^{-1}$, the expected wind speed ("wnd spd") can be entered in units of mph, $km \cdot hr^{-1}$, $ft \cdot sec^{-1}$ or knots. Calm, breezy or windy conditions are categorized as 0.5, 2.0 and 4.0 $m \cdot s^{-1}$, respectively.

The third row of keys below the prefix keys address the impact of the solar heat load. The internal parameters used in considering solar heat load were developed from the concept of mean radiant temperature (Gagge, 1970) as applied to clothing heat exchange by Breckenridge and Goldman (1971). Categorizations are cloudy, partly cloudy ("prt cloudy") or clear sky with allowance for the indoors where there is no appreciable solar load.

The output keys are at the bottom of the calculator. The "wrk cycle" key provides output for the calculated work-rest cycle, and the one time only maximum work period with time periods in minutes. The "water reg" key allows the user to compute the water requirements during work, rest and combined in canteens per hour or quarts per hour. One of the output keys remains uncommitted and remains available for future use. Hopefully, the military user can employ this calculator to help avoid unnecessary casualties associated in the environmental heat extremes, and by predicting appropriate work-rest cycles and water requirements facilitate the achievement of mission objectives.

ACKNOWLEDGEMENTS

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FIGURE LEGENDS

FIGURE 1. Comparison of predicted (lines) and measured (x) patterns of rectal temperature during one hour cycles of rest, exercise and recovery as published by Givoni and Goldman (1972). Subjects wore shorts, standard fatigue uniforms (STD) or protective overgarments over fatigues (OG) in climatic conditions of either 35° or 49°C ambient temperature with vapor pressures of 20 or 30 mm Hg at wind speeds of 0.5 m·s^{-1}.

FIGURE 2. Comparison of predicted (lines) and measured (dots) patterns of rectal temperature as a function of day of acclimation for soldiers walking for an attempted 100 min at 49°C, 20% rh as published by Givoni and Goldman (1973b).

FIGURE 3. Comparison of predicted and observed rectal temperature responses of 12 soldiers while wearing three different military clothing systems each under two different climatic conditions.

FIGURE 4. Relationship between predicted and measured sweat loss for 111 individual responses as published by Shapiro et al. (1982).

FIGURE 5. Comparison of four methods of predicting sweat loss using data from our Division as published by Shapiro et al. (1982). The solid line represents the line of identity while the dashed lines represent the +20% range from the line of identity.

FIGURE 6. Relationship between predicted and measured final heart rate responses: left, from our own Division studies; right, from observations by Macpherson (1960) and Wyndham et al. (1954) as published by Givoni and Goldman (1973a).
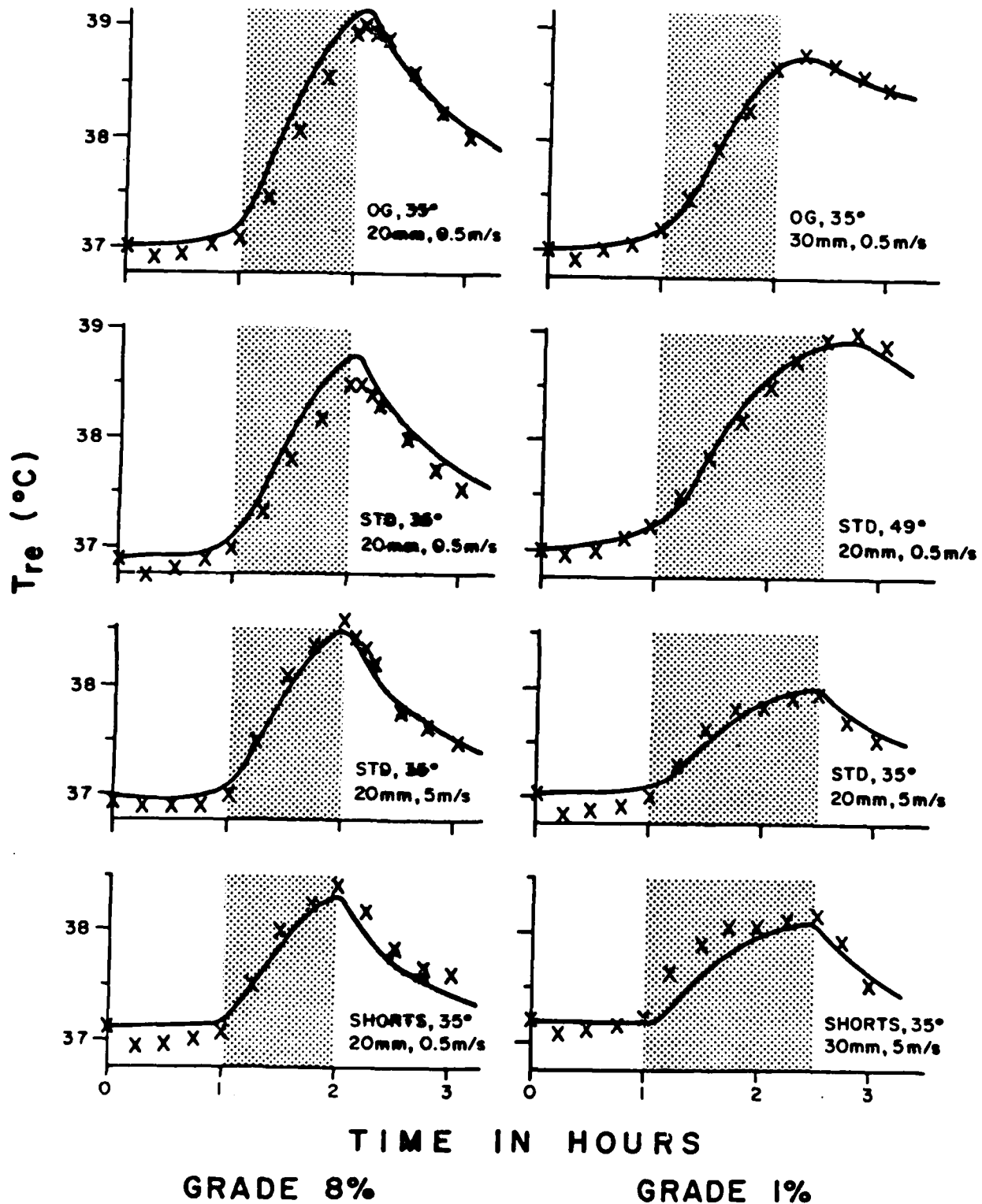
FIGURE 7. The redesigned touch pad of the Hewlett Packard 41 CV which encompasses the input parameters of our heat stress prediction model.
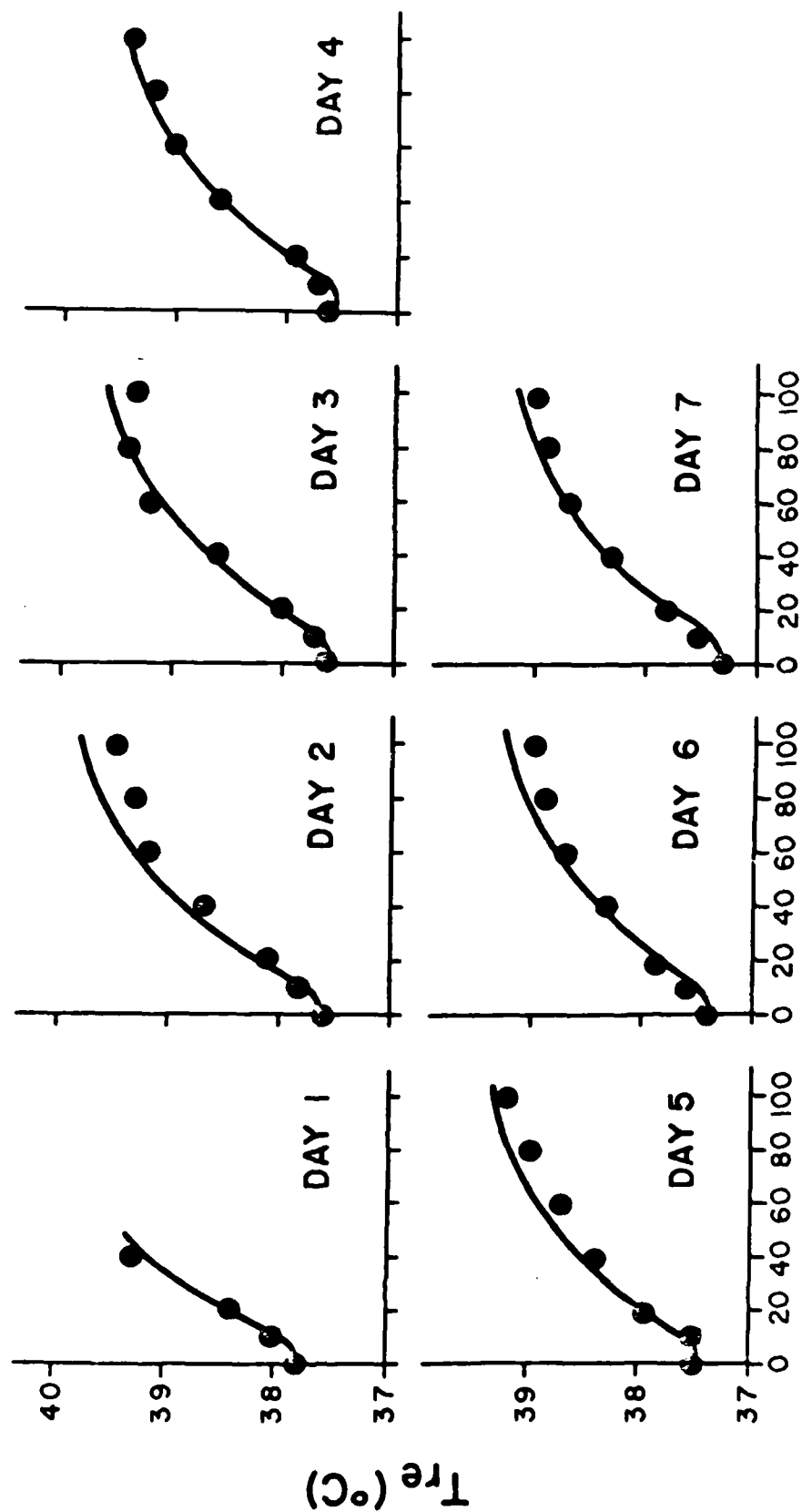
TABLE 1.   CLOTHING MENU

DISPLAY	DESCRIPTION
1. :AVIAT	Aviators
2. :AVIAT+ARM	Aviators + armor (mask+hood)
3. :AV+OG+ARM	Aviators +OG+armor (MOPP IV)
4. :AV+UK+UNDW	Aviator+UK underwear (MOPP IV)
5. :BDO+RAIN	BDO + rainsuit
6. :BDU	BDU
7. :BDU+ARMOR	BDU + armor
8. :BDU+RAIN	BDU + rainsuit
9. :CVC	CVC
10. :CVC+CBR, MI	CVC + CBR (MOPP I)
11. :CVC+CBR, MIV	CVC + CBR (MOPP IV)
12. :DESRT CAMOF	Desert camouflage
13. :DESERT TAN	Desert tan
14. :EOD+FATIGUE	EOD over fatigues
15. :FIRE+FATIG	Firefighters over fatigues
16. :FUEL HANDLR	Fuel handlers (TAP)
17. :MOPP I	MOPP I
18. :MOPP II	MOPP II
19. :MOPP III	MOPP III
20. :MOPP IV	MOPP IV
21. :PONCH+FATIG	Poncho over fatigues
22. :TROP CAMOFL	Tropical camouflage
23. :TROP FATIG	Tropical fatigues
24. :TROP FA+ARM	Tropical fatigues + armor
25. :UTIL FATIG	Utility fatigues

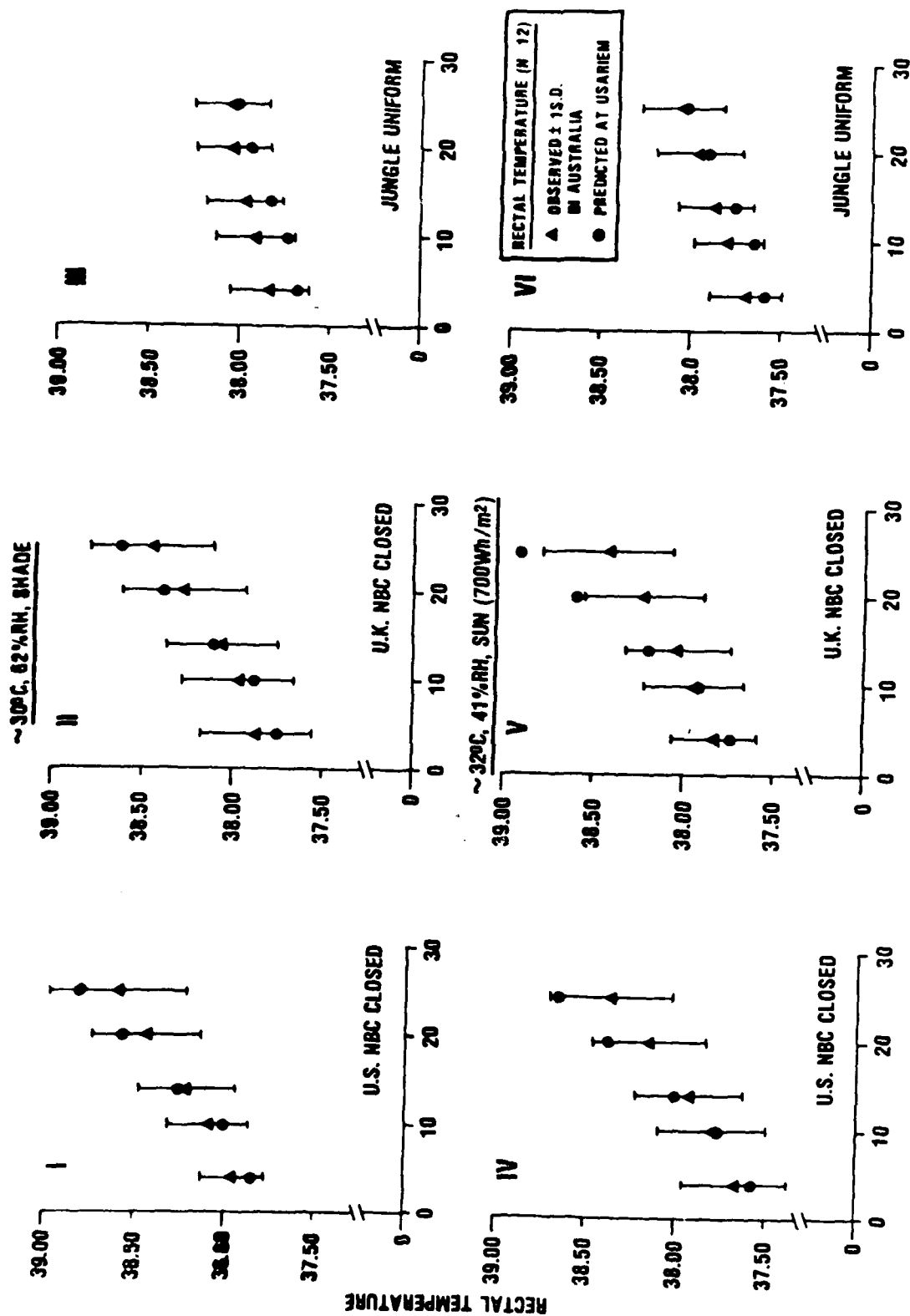TABLE 2.   MULTIPLICATION FACTORS FOR ENERGY COST
            AS A FUNCTION OF TERRAIN

TERRAIN	η
BLACKTOP SURFACE	1.0
DIRT ROAD	1.1
LIGHT BRUSH	1.2
HARD PACKED SNOW	1.3
HEAVY BRUSH	1.5
SWAMPY BOG	1.8
LOOSE SAND	2.1
SOFT SNOW	1.3+0.08 (CMS. OF SNOW PRINT DEPTH LEFT BY FOOT)

GIVONI AND GOLDMAN, 1972
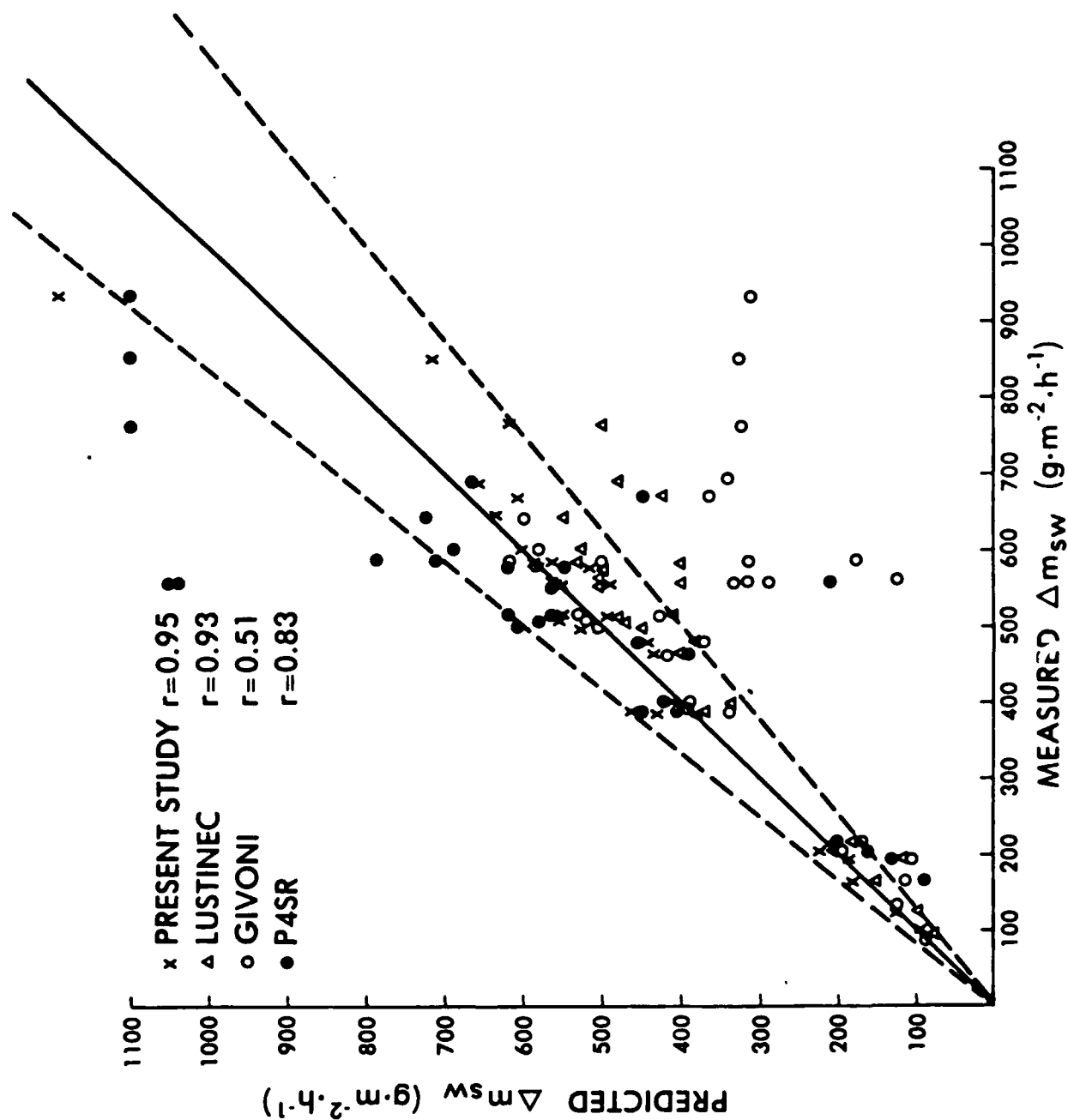
OG, 35°
20mm, 0.5m/s

OG, 35°
30mm, 0.5m/s

STD, 35°
20mm, 0.5m/s

STD, 49°
20mm, 0.5m/s

STD, 35°
20mm, 5m/s

STD, 35°
20mm, 5m/s

SHORTS, 35°
20mm, 0.5m/s

SHORTS, 35°
30mm, 5m/s

T_{re} (°C)

TIME IN HOURS

GRADE 8%   GRADE 1%

26

DAY 1 DAY 2 DAY 3 DAY 4

DAY 5 DAY 6 DAY 7

T_{re} (°C)

TIME (MINUTES)

GIVONI AND GOLDMAN, 1973

RECTAL TEMPERATURE (N = 12)

▲ OBSERVED ± 1 S.D.
  IN AUSTRALIA
● PREDICTED AT USARIEM

GOLDMAN, 1981

28

MEASURED Δm_{sw} $(g \cdot m^{-2} \cdot h^{-1})$

PREDICTED Δm_{sw} $(g \cdot m^{-2} \cdot h^{-1})$

r=0.94

Shapiro, et al 1982

PREDICTED Δm_{sw} ($g \cdot m^{-2} \cdot h^{-1}$)

MEASURED Δm_{sw} ($g \cdot m^{-2} \cdot h^{-1}$)

Shapiro, et al 1982

x PRESENT STUDY r=0.95
△ LUSTINEC r=0.93
○ GIVONI r=0.51
● P4SR r=0.83

31
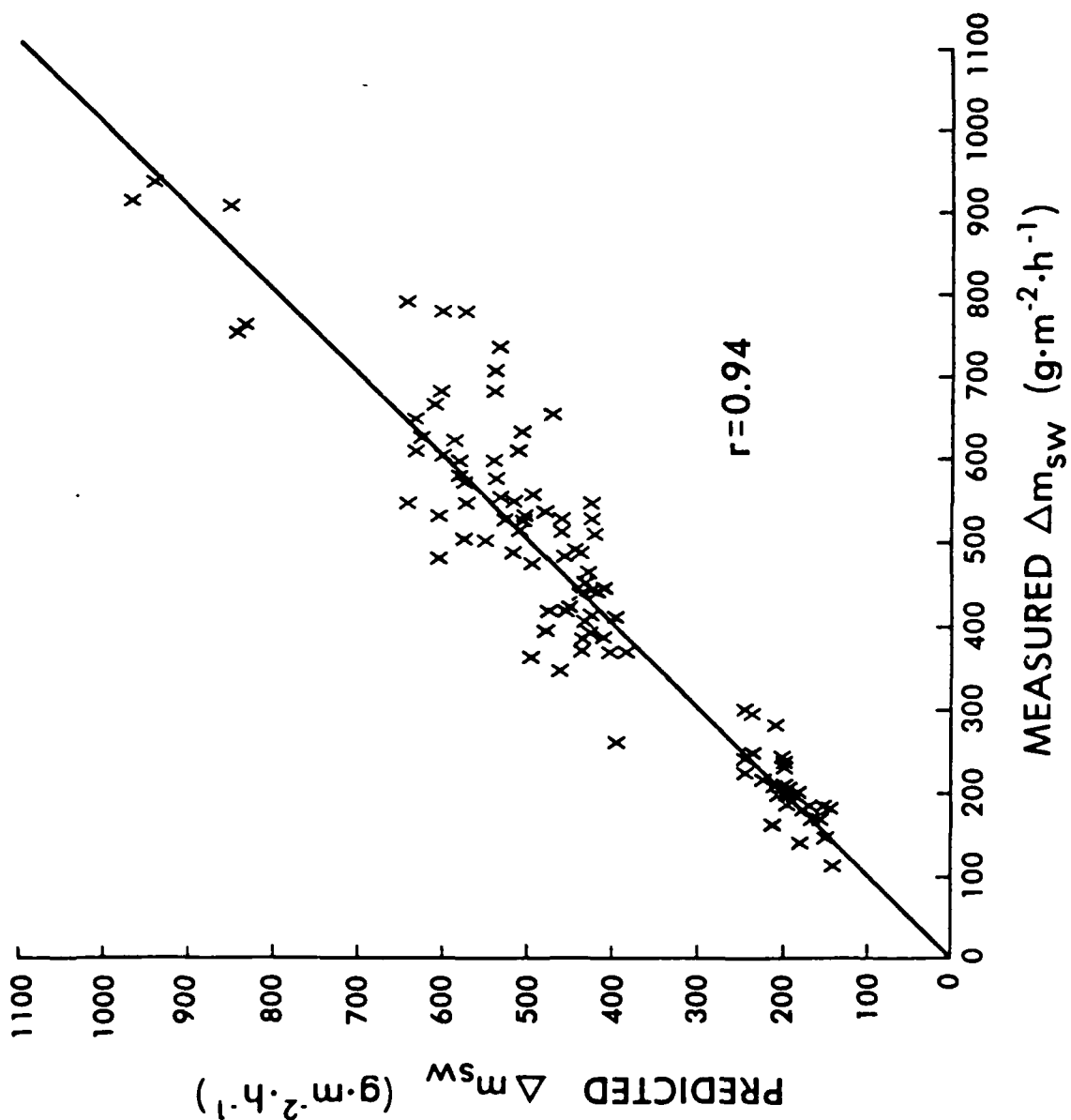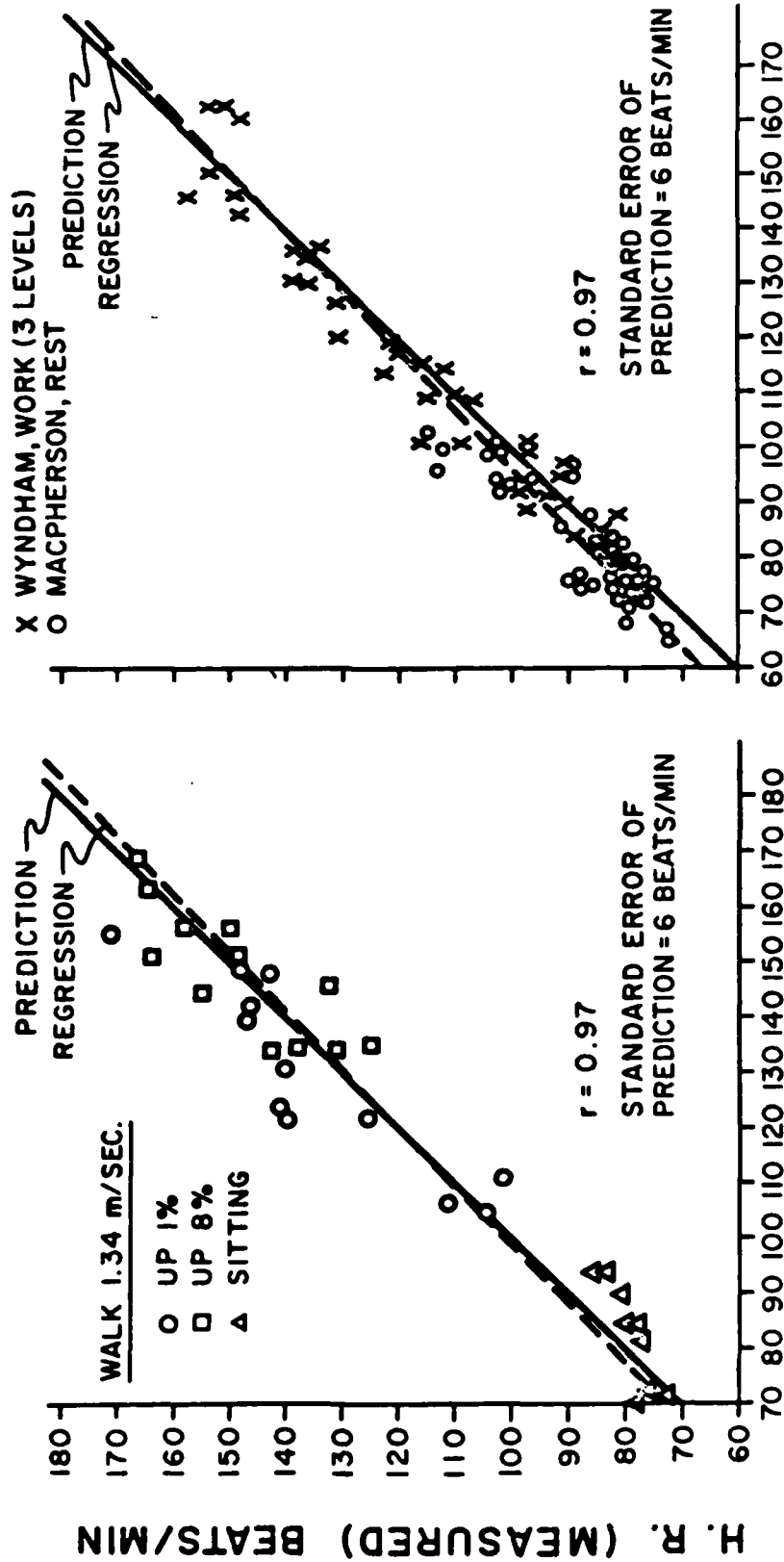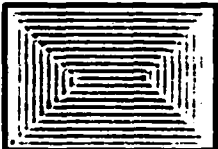
GIVONI AND GOLDMAN, 1973

**** DISPLAY ****

on/off	user		program	alpha

A	B	C	D	E
MOPP I	MOPP II	MOPP III	MOPP IV	CLOTH MENU

F	G	H	I	J
WORK LIGHT	WORK MOD	WORK HVY	METAB.RATE	FUNC 0

	K	L	M	NON-ACCL
	CASLT LIGHT	CASLT MOD	CASLT HVY	ACCL

N	O	P	
SELECT	DISP	COMP	DISP UNITS

Q	R	S	T
Ta	% RH	HOT WET	HOT DRY
	7	8	9

U	V	W	X
WIND SPEED	CALM	BREEZY	WINDY
	4	5	6

Y	Z	=	?
CLOUDY	PARTLY CLOUDY	CLEAR SKY	INDOORS
	1	2	3

:		,	
WRK CYCLE	WATER REQ		RUN
	0	.	

END

FILMED

12-85

DTIC